

THE DARKER SIDE

Decoupling Capacitors and RLC Networks

V1
U=1 V

Pr2

Pr1

R=0.1 Ohm

L1
L=1R2
R=0.1 Ohm

C=1 pF

COLUMNS

In some situations, decoupling capacitors can increase the noise on power supply lines. In this article, Robert introduces the subjects of decoupling capacitors, parasitic RLC networks, and parallel LC networks.

By Robert Lacoste

Welcome back to the Darker Side. Reading a good book is a wonderful source of inspiration. A book of fiction from a Swedish author might motivate you to immediately buy a ticket to Stockholm. A biography can help a teenager to find his career. A cookbook can even help to avoid a divorce. More often than not, reading a good technical book is also a rewarding experience. It can even create the “wow effect.” You think you know something, and you suddenly discover an explanation that highlights the subject from a clever viewpoint and makes things more evident. I recently had this experience while reading a great book by Douglas Brooks, president of UltraCAD Design. His easy-to-read book, *Signal Integrity*

Issues and Printed Circuit Board Design, deals with subjects ranging from EMI mitigation to signal integrity. What really grabbed my interest was a chapter on strange issues associated with decoupling capacitors. In some situations, adding decoupling capacitors can increase the noise on power supply lines. You don’t trust me? Well, keep reading. I will provide an overview of the subject, even though I’m sure you’ll buy and read Brooks’s book.

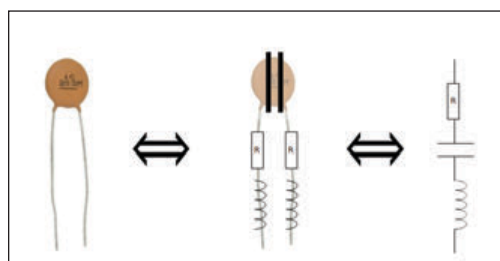
DECOUPLING CAPACITORS?

Ok, let’s start. You know that so-called decoupling capacitors must be included in all designs, particularly between each power supply line and a PCB’s ground plane. These decoupling capacitors help to filter out transients and noise circulating on the power supplies. If not, these noises can either jeopardize the system’s performance or cause serious headaches during electromagnetic compatibility tests.

In order to be efficient, such a filtering must be performed as close as possible to the potential noise sources: digital circuits, fast clocks, switching elements, etc. Similarly, the

FIGURE 1

Any capacitor has in fact parasitic inductors and resistors, so it is equivalent to a serial RLC network.



same kind of filtering must be added as close as possible to potential victims like sensitive analog circuits. Therefore, the usual rule is to include enough decoupling capacitors so that at least one capacitor is close to each chip on the board.

So the designer usually includes one decoupling capacitor, typically around 100 nF, close to each chip. Is it enough? Maybe not, because noise on a power line can be wideband. For example, imagine a PC motherboard with noise ranging from some kilohertz (e.g., video interface or switching power supply) to gigahertz (e.g., processor and DRAM clock speed and their harmonics). The problem is that a 100-nF capacitor, even a good one, is only adequate for a small frequency range. Why? For very low frequencies, a higher capacitor value is needed as a larger “energy tank” is required, so some 100 μ F or so may be needed on the board too. However, and this may be less intuitive, such a 100-nF capacitor is also not adequate above a given frequency. Let’s investigate why.

PARASITIC RLC NETWORKS

Old-time readers, please forgive me, as I already devoted a column on that topic (“Parasitic Components,” *Circuit Cellar* 245, 2010). The problem is linked to parasitic components inevitably part of any actual

capacitor. Connecting wires or pads, as well as the internal structure of the capacitor, aren’t perfect. They behave as small series inductors with an additional small series resistor (equivalent serial resistor, or ESR), so a capacitor is actually more or less a serial RLC network (see **Figure 1**).

Let’s take the example of a 470-nF capacitor and assume that the serial parasitic components are respectively $L = 10$ nH and $R = 0.1 \Omega$. These are indeed typical values for a surface-mounted, 470-nF capacitor. What is the impedance of such a capacitor across a wide-frequency band? You can do the calculations using the formulas found on any electrical engineering textbook, but I preferred to perform a small simulation for you using the free QUCS circuit simulator. In order to plot an impedance using such a simulator, just remember that $Z = U/I$. You have to launch the simulator, add a virtual signal source and connect RLC components of the proper values. Then add virtual meters to measure the voltage U and current I flowing through the RLC network, and write an equation to calculate Z . Click on “Simulate,” and voila.

Look at **Figure 2**. The simulation shows the impedance of this RLC network from 10 kHz up to 1 GHz, as well as the respective impedances of the resistor, inductor, and

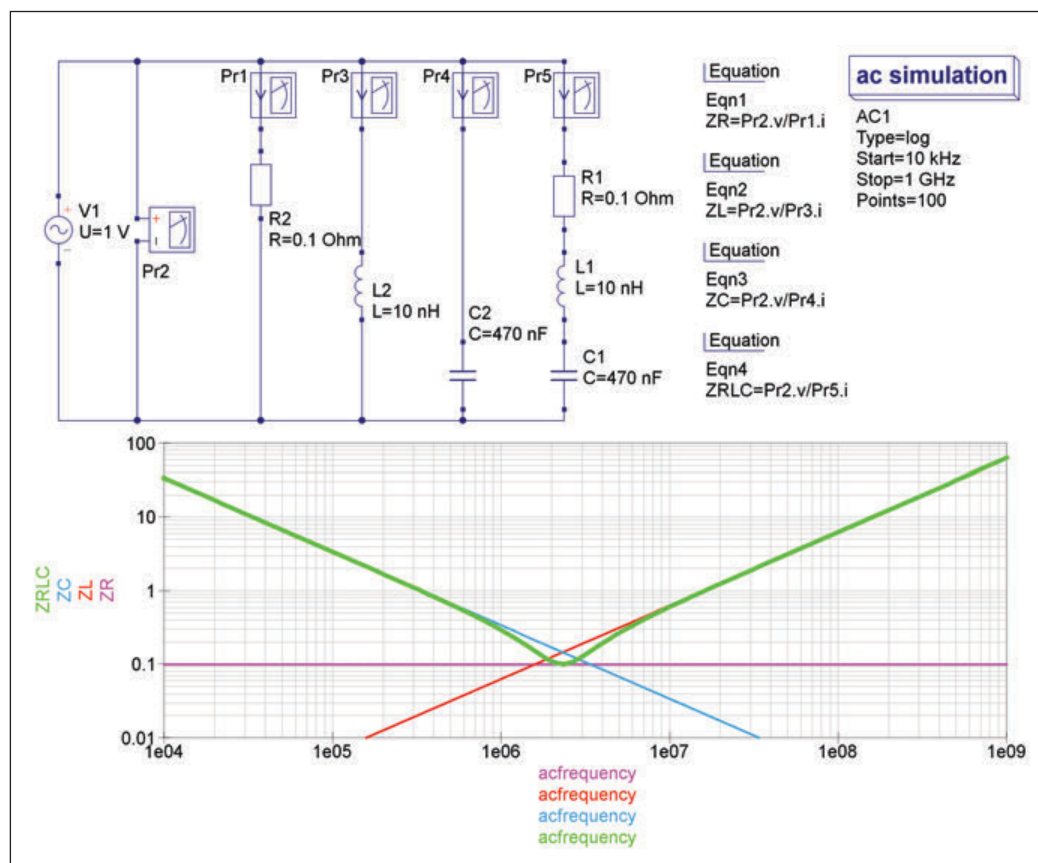
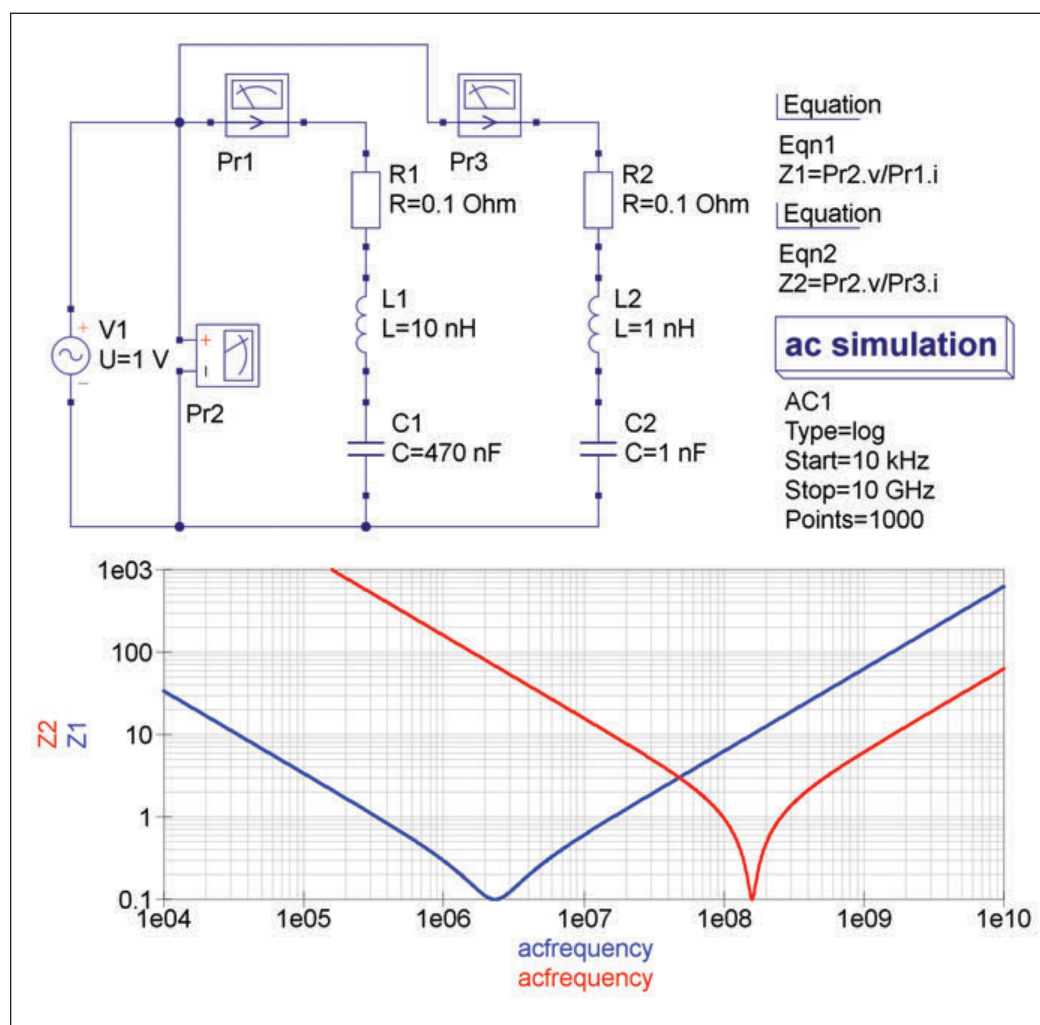


FIGURE 2

This QUCS simulation shows the impedance from 10 kHz to 1 GHz of a resistor (pink), perfect capacitor (blue), and inductor (red), as well as the impedance of the resulting RLC network (green).

FIGURE 3

Different capacitors have different resonant frequencies. Here we have 2.3 and 160 MHz, respectively.



capacitor alone. As expected, the impedance of the capacitor (in blue) gets lower and lower when the frequency increases, and the impedance of the RLC network (in green) is nearly the same than the capacitor alone up to some megahertz. However, something strange happens at a given frequency. Here it's a little above 2 MHz (actually, $1/(2\pi\sqrt{LC})$, which gives 2.3 MHz). The impedance of the RLC network is no longer decreasing with frequency but increasing. In fact, above

5 MHz, it is nearly the same impedance as the parasitic inductor alone (in red). At the crossover frequency (i.e., the resonant frequency of the RLC network), the L and C cancel each other and the network is purely equivalent to the series resistance.

In a nutshell, any capacitor is a capacitor only up to its resonant frequency. Above this frequency it behaves as an inductor. That's why a single capacitor is usually not enough to filter out a wide-band noise like noise on a power supply rail, and that's why you often find on schematics several capacitors of different values in parallel, like $10\ \mu\text{F} + 100\ \text{nF} + 10\ \text{pF}$. Each capacitor is useful in a different frequency band. Here the $10\ \mu\text{F}$ is very efficient in low frequencies, but it will very probably have a resonant frequency of some tens of kilohertz as it has large electrodes with high parasitic inductance. The $100\ \text{nF}$ takes the lead then, up to 1 MHz or so, and a small 10-pF capacitor filters out the higher frequencies.

TWO CAPACITORS IN PARALLEL

Now, the funny part. Assume that you have

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a 470-nF decoupling capacitor (with 10 nH + 0.1 Ω parasitics as above), but you experience too much noise above 1 MHz. You read Circuit Cellar, so you know you must add a smaller capacitor in parallel, which will provide a smaller parasitic inductance and will then help to damp out the high frequency noise. Assume that you select a 1nF capacitor with 1nH parasitic inductance and the same 0.1- Ω ESR. If you calculate the impedance of each capacitor independently you will get two “V” shaped curves (see **Figure 3**). The 470 nF has a resonant frequency of 2.3 MHz, while the 1 nF resonates at 160 MHz, so board in parallel will provide a nice rejection up to 160 MHz, right?

Wrong, because RLC networks are a bit more insidious. Look at **Figure 4**, which shows the impedance of these two capacitors connected in parallel. As expected, up to 2.3 MHz the behavior is the same than a 470-nF capacitor alone. Similarly, above 160 MHz the inductive part of the 1-nF capacitor predominates. But what is this strange behavior between these two frequencies? If you compare Figure 3 and Figure 4, you will see that at a specific frequency—close to 50 MHz in this case—the impedance of the two

capacitors, connected in parallel, is as high as 50 Ω . This is far higher than the impedance of each capacitor alone (3 Ω or so each)! How can we have two parts, each having an impedance of 3 Ω , showing a 50- Ω impedance when connected in parallel?

PARALLEL LC NETWORK

Even if this seems strange, the simulation is not faulty, impedances are just a bit more difficult to manage than simple resistances. There is effectively a frequency range, here around 50 MHz, where two capacitors in parallel provides less filtering than any of these two capacitors alone. Let me explain why. As discussed, the larger capacitor, here 470 nF, behave as a capacitor up to its resonant frequency of 2.3 MHz. Above that limit, it behaves like an inductor. So, at 50 MHz, the 470-nF capacitor is in fact an inductor equal to the parasitic inductance of the capacitor (10 nH). At this frequency, the 1-nF capacitor is still a capacitor. So, the assembly of the two capacitors in parallel is equivalent to a parallel LC network around 50 MHz and no longer to two RLC serial networks.

Do you know what is the impedance of a parallel LC network with $L = 10$ nH and C

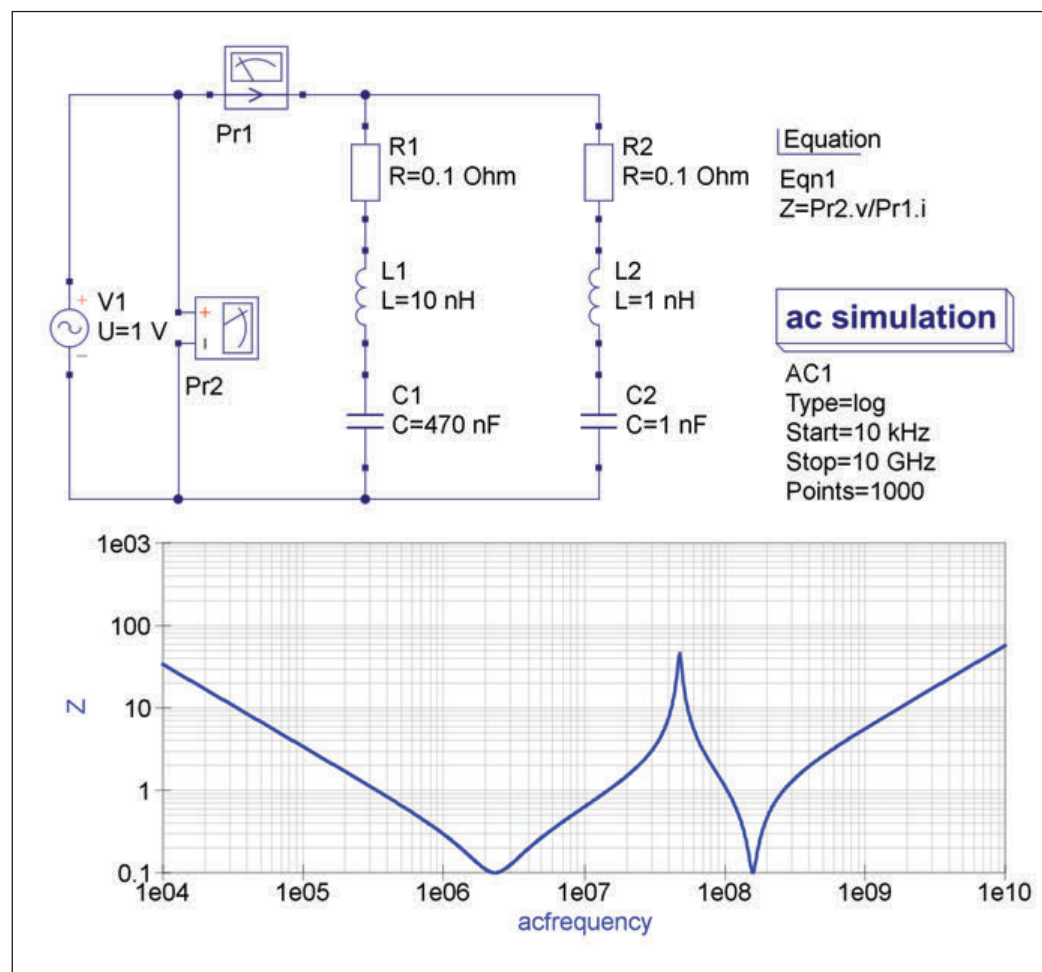
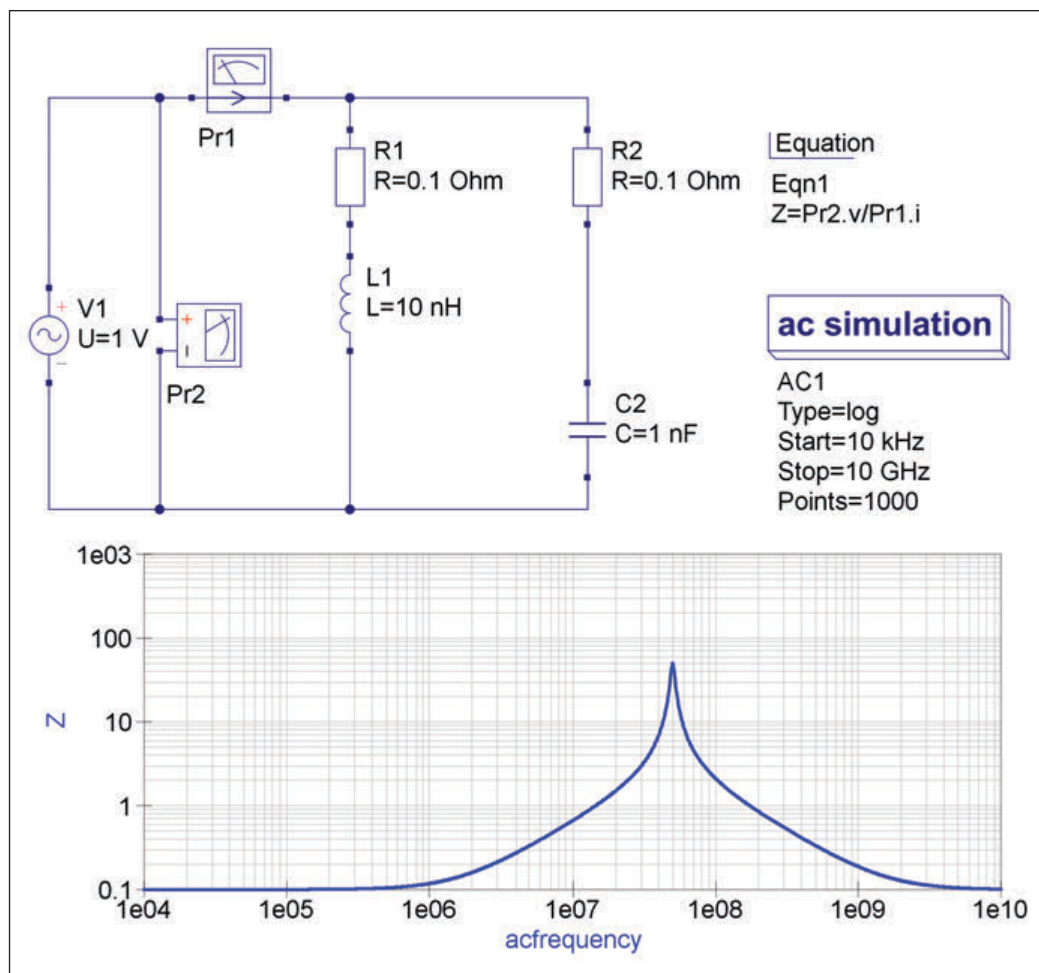


FIGURE 4

Two capacitors in parallel introduce a nasty phenomenon. At a given frequency, the overall impedance gets far higher than the impedance of each capacitor alone.

FIGURE 5

This is the simulated impedance of a parallel LC network. Here the 470-nF capacitor is assumed to be equivalent to its parasitic inductance, whereas the 1-nF capacitor is still a capacitor.



= 1 nF and with some ESR? Just ask QUCS again and you will get the simulation result shown on **Figure 5**. Does it look familiar? You bet so, this is exactly what we got for frequencies between the resonant frequencies of both capacitors. This is evident when you compare it to Figure 4. So, such a parallel LC network forms a pass-band filter. It has a low impedance except close to its resonant frequency. By the way, this resonant frequency is here also calculated as $1/(2\pi\sqrt{LC})$, which gives 50.3 MHz as expected.

SOLUTIONS?

It is now time to summarize what we learned. Decoupling capacitors are used to reduce noise on signals and power supply

lines. As noise can be wideband, these decoupling capacitors must be efficient on a wide frequency range. Unfortunately, a capacitor has always some parasitic series inductance and ESR, which transform it into a series RLC network. So a capacitor is no longer a capacitor above its resonant frequency.

How can you increase the attenuation frequency range? Connecting N capacitors of the same value in parallel effectively reduces the overall impedance by a factor of N, thus improving the noise attenuation, but this doesn't increase the resonant frequency. Just verify it as a homework. Tip: capacitance is multiplied by N, but serial inductance is divided by N.

So, the only solution is to connect several capacitors of different values, still in parallel. However, this introduces parallel LC resonance modes, which could drastically reduce the attenuation for frequencies between the series-resonant frequencies of each capacitor.

Now it's time to introduce Murphy's law in our discussion (nearly equivalent to Sod's law). You know, it states that if anything can go wrong, it will. The corollary is the following: if your design has a noise issue



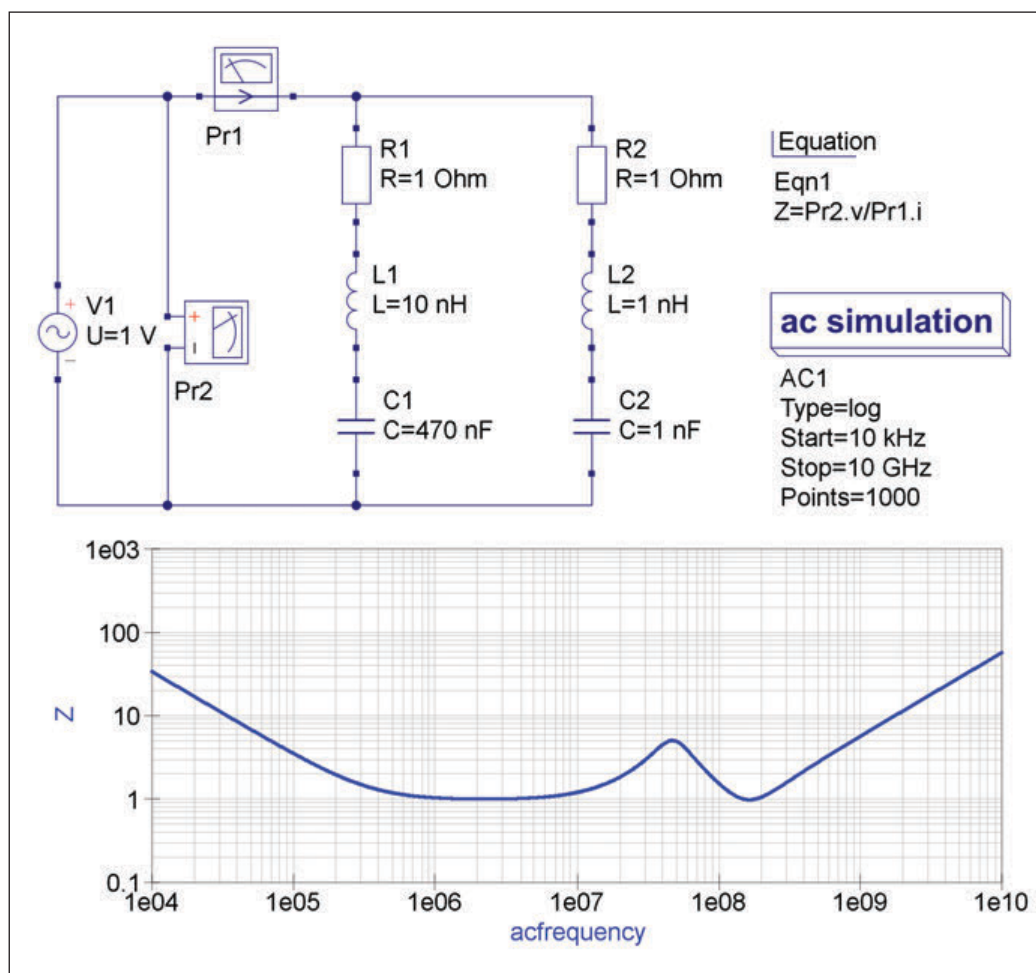
circuitcellar.com/ccmaterials

RESOURCE

D. Brooks, *Signal Integrity Issues and Printed Circuit Board Design*, Prentice Hall, 2003.

SOURCE

Quite Universal Circuit Simulator
QUCS | <http://qucs.sourceforge.net/>

**FIGURE 6**

Higher ESR provides a smoother frequency response.

at a given frequency, and if you add more decoupling capacitors to help filter out the noise, then you will definitely introduce a nasty parallel resonance mode that will increase the noise exactly at the frequency at which you don't want noise. How can you avoid or limit this risk? One solution is to add plenty of capacitors of random capacitance all over the board. Statistically, you may get a flatter frequency attenuation, but you can also encounter difficult problems if you are unlucky. Another good solution, even if it seems awkward, is to avoid using good capacitors as decoupling capacitors. More specifically, for decoupling applications, it is better to select capacitors with intermediate ESR rather than ultralow ESR parts. Do you need convincing? Look at the last simulation shown in **Figure 6**. I used exactly the same 470 nF + 10 nH and 1 nF + 1 nH capacitors, but increased their ESR from 0.1 to 1 Ω . Compare this simulation to Figure 4. The minimum impedance is, of course, increased from 0.1 to 1 Ω , but the maximum impedance at the parallel LC resonance is reduced from 50 down to 7 Ω , giving a smoother impedance curve. This shouldn't be a surprise, as a higher ESR reduce the

quality factor of the capacitors, and a lower quality factor provides wider frequency responses.

WRAPPING UP

I'm out of space, but this apparently simple problem can fill books. I hope it's clear that capacitors are a bit funnier than you might have assumed, and that decoupling can lead to some surprises. As always, you have two options when you discover such strange behavior, even if this happens only hours before the committed delivery of a project (Murphy's law again). Option 1: You can call it "black magic," stop trying to understand it, and redo the design differently with the hope that things will get better. Option 2: You can experiment in an effort to try to understand what's going on and then refer to good books to get more insight on the problem. Option 2 may take a little more time, but it will surely improve your knowhow and expertise. It could be fun too.

So, if you want to go further, I suggest Douglas Brook's book. You will learn why it's better to also use the PCB as a capacitor—that is, to include large parallel ground planes and power planes. And have fun! 